

**APPARATUS, AND AN ASSOCIATED METHOD, FOR FACILITATING  
SYNCHRONIZATION IN A WIRELESS MESH NETWORK.**

The present invention relates generally to a manner by which to facilitate time synchronization between nodes of a mesh network, such as a fixed broadband access network or a moving ad hoc mesh network. More particularly, the present invention relates to apparatus, and an associated method, by which to provide accurate time reference indicia to the nodes of the mesh network to permit time and clock synchronization pursuant to a synchronization hierarchy. Time stamps are added to data packets at a node at which an updated time reference value is maintained. When sent to another node, the time stamp is extracted to provide the other node with the updated time reference value. The time reference value is buffered and updated at a register and selectively retrieved therefrom to form the time stamp.

**BACKGROUND OF THE INVENTION**

Communication of data between remotely-positioned sending and receiving stations is a necessary adjunct of modern society. A wide variety of different types of communication systems have been

developed and are regularly utilized to effectuate communication of data between the sending and receiving stations.

Communication technology advancements have permitted the development, and commercial implementation, of new types of 5 communication systems. Radio communication systems are exemplary of communication systems which have benefited from the advancements in communication technologies. Improvements to existing types of radio communication systems, as well as new types of radio communication systems, have been made possible as a result of the 10 advancements in communication technologies.

Use of a radio communication system inherently permits increased communication mobility in contrast to use of a conventional wireline communication system. Communication channels defined between sending and receiving stations of a radio 15 communication system are defined upon radio links formed therebetween. The communication channels are referred to as radio channels and do not require fixed connections for their formation.

The advancements in communication technologies which have 20 permitted the development and implementation of new types of communication systems include, for instance, digital communication

techniques. The use of digital communication techniques permits the communication capacity of a communication system to be increased as well as also to improve the quality levels of communications effectuated in the communication system.

5       Information which is to be communicated in a digital communication system is digitized. Once digitized, the digitized information is formatted, such as into packets of data, referred to as data packets. Data packets are sent by a sending station upon the radio channel to the receiving channel, thereby to effectuate the communication of the data packets therebetween. Individual ones, or groups, of the packets can be communicated at discrete intervals, and, once communicated, the packets of data can be concatenated together to recreate the informational content of the transmitted information.

15      Because the packets of data can be sent at discrete intervals, a radio, or other, communication channel need not be dedicated solely for the communication of data pursuant to a single communication session between one sending station and one receiving station. A dedicated channel, in contrast, is required in conventional circuit-switched communications. In packet-switched communications, a single channel can be used pursuant to the

effectuation of a plurality of different communication sessions. Improved communication capacity is possible due to the shared nature of the communication channels permitted in packet-switched communications.

5       A wireless mesh network is a radio communication system which can be constructed to provide for the communication of packet data pursuant, e.g., to a digital communication technique. A wireless mesh network typically includes a plurality of nodes, each node capable of communicating with at least one other node. A wireless mesh network is implemented, for instance, as a fixed broadband access network capable of communicating broadband data between fixed-site communication stations which form the nodes. A moving ad-hoc mesh network is also representative of a wireless mesh network.

15      Network synchronization is necessary in a wireless mesh network to properly utilize the radio resources available to communicate thereon. Transmission and reception scheduling is conventionally utilized in a wireless mesh network. Scheduling is required to ensure that the nodes of the network be synchronized in 20 time. Through appropriate time synchronization, guard intervals separating communications upon a radio link can be reduced as the

synchronization limits the amount of drifting of bursts of packet data beyond a defined transmission period. Without proper synchronization, guard intervals of increased sizes are required, thereby reducing the communication capacity upon the radio links 5 formed between nodes of the network.

In a mesh network, a formal hierarchy is not necessarily defined. And, if a hierarchy is defined, reference distribution, pursuant to which synchronization is performed, is implemented hierarchically. Reference errors increase accumulatively in successive branches of the hierarchically-defined structure.

A manner by which to provide a systematic reference by which to effectuate time synchronization in a mesh network, such as a fixed broadband access network or a moving ad-hoc mesh network would therefore be advantageous.

It is in light of this background information related to communications in a mesh network that the significant improvements of the present invention have evolved.

#### **SUMMARY OF THE INVENTION**

The present invention, accordingly, advantageously provides 20 apparatus, and an associated method, by which to facilitate time

synchronization between nodes of a mesh network, such as a fixed broadband access network or a moving ad-hoc mesh network.

Through operation of an embodiment of the present invention, accurate time reference indicia is provided to the nodes of the 5 mesh network to permit time and clock synchronization pursuant to a synchronization hierarchy.

An updated time reference value is maintained at a node of the mesh network. The time reference value is used as a time stamp which is added to data packets which are to be communicated by the 10 node to another node. When sent to the other node, the time stamp is extract to provide the other node with the updated time reference value. The time reference value is maintained at the first node at a register and is selectively retrieved therefrom to be used the time stamp.

15 In one aspect of the present invention, a network time register is positioned at a first node formed of a first communication station of the mesh network. A clock signal is applied to the network time register, and the contents of the network time register are incremented, either positively or 20 negatively, thereby to maintain an update at the register of an updated time reference value. At least selected data packets are

time-stamped with time reference values retrieved from the network time register. When the data packets are communicated to a second, or other, node formed of another communication station, the time stamp is extracted from the data packet and used to time 5 synchronize the other communication station to the first communication station.

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Delay between the send time, i.e., the time at which the data packet is sent by the first communication station and the receive time, i.e., the time at which the data is received at the second communication station, is compensated for by calculation of the transmission duration. Calculation is made by returning a data packet from the second communication station to the first communication station. The time at which the returned data packet is received at the first communication station permits determination of the transmit time between the two communication stations. An additional data packet is sent to the second communication station to inform the second communication station of the transmission time period and the corresponding alteration of the time reference value which should be maintained at the second communication station.

In another aspect of the present invention, an additional register, a latch register, is also formed at the first communication station. The network latch register is coupled to the network time register, and time reference values buffered and 5 maintained at the network time register are also selectively storable at the network latch register. The values are retrieved and latched thereat upon application to the latch register of a trigger signal. When the trigger signal is applied to the latch register, the contents of the network time register are copied thereto.

In another aspect of the present invention, a network strobe register is also formed at the first communication station. The strobe register is also coupled to the network time register to receive values of the reference time stored thereat. The strobe register counts out and generates a signal which forms the trigger signal when the register counts out. Thereby, at periodic 15 intervals, when the strobe register counts out, a trigger signal is generated and applied to latch register.

Registers, either implemented as hardware devices or as 20 software devices, formed at a communication station in a mesh network provide a manner by which to maintain, and update, a time

reference value. By time-stamping selected data packets which are communicated by the communication station to another communication station, time synchronization therebetween is provided. And, when successive nodes, i.e., communication stations of the mesh network 5 include such registers, network-wide synchronization is implementable. A pseudo-hierarchy is also provided by defining a one of the communication stations to maintain the reference time value.

In these and other aspects, therefore, apparatus, and an associated method, is provided for a wireless mesh network having a first communication station and at least a second communication station. Time-synchronization of communication of data between the first and least second communication stations is provided. A network time register is coupled to receive a time reference signal of values representative of a reference time. The network time register buffers and maintains updated values of the reference time. A data formatter is coupled to the network time register. The data formatter formats the data to be communicated between the first and least second communication stations of the wireless mesh 15 network. The data, once formatted, includes indicia associated 20

with the updated values of the reference time buffered at the network time register.

A more complete appreciation of the present invention and the scope thereof can be obtained from the accompanying drawings which 5 are briefly summarized below, the following detailed description of the presently-preferred embodiments of the invention, and to the appended claims.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

Figure 1 illustrates a functional block diagram of an exemplary wireless mesh network in which an embodiment of the present invention is operable.

Figure 2 illustrates a functional block diagram of exemplary network timing circuitry of an embodiment of the present invention.

Figure 3 illustrates a functional block diagram, similar to 15 that shown in Figure 2, of timing circuitry of an alternate embodiment of the present invention.

Figure 4 illustrates a functional block diagram of an implementation of the timing circuitry of the embodiment shown in Figures 2 and 3.

Figure 5 illustrates a functional block diagram of clock synchronization circuitry of an embodiment of the present invention.

Figure 6 illustrates a method flow diagram of the method of 5 operation of an embodiment of the present invention.

Figure 7 also illustrates a method flow diagram, also representative of the method of operation of an embodiment of the present invention.

Figure 8 illustrates a representation of communications 10 between first and second nodes of the exemplary wireless mesh network shown in Figure 1.

**DETAILED DESCRIPTION OF THE INVENTION**

Referring first to Figure 1, an exemplary wireless mesh network, shown generally at 10, provides for wireless communications between a plurality of nodes 12 which collectively 5 form the mesh network. In the exemplary implementation, the wireless mesh network forms a fixed wireless broadband access network. In another implementation, the mesh network 10 is representative of a mobile ad-hoc network.

Each of the nodes 12 forms a wireless communication station capable of transceiving communication signals with other communication stations. When the mesh network provides for packet data communications, the communication stations are operable to communicate packet data therebetween.

While a mesh network does not necessarily contain a hierarchy, the mesh network 10 shown in the figure defines a pseudo-hierarchy relative to a center (as-shown) communication station 12-C. The communication station 12-C forms a reference node. Distances from the reference node from other nodes are defined in terms of hops.

With respect to the reference node 12-C, a first set of nodes 20 formed of communications, in here shown at 12-1 are positioned at one-hop distance from the reference node 12-C. Another set of

communication stations formed for the nodes, here shown at 12-2, are two-hop distances from the reference node 12-C. And, a third set of communications stations formed of the nodes, and here shown at 12-3 are at three-hop distances from the reference node 12-C.

5 Nodes 12-4 and 12-5 are analogously numbered responsive to their respective hop distances from the reference node.

While only a single reference node 12-C is represented in Figure 1, a pseudo-hierarchy formed of multiple references can also be defined in a wireless mesh network. In such an implementation, the simplistic hop-distribution shown in Figure 1 with respect to a signal reference node is not utilized. But, in such an implementation, a single node synchronizes, for example, to its neighbors with a lowest distance to a reference node.

10 To provide for efficient utilization of the radio resources allocated to the mesh network, appropriate levels of time synchronization are required to be effectuated in the mesh network. An embodiment of the present invention provides for time and clock synchronization pursuant to a pseudo-hierarchy which provides appropriate levels of synchronization between the nodes of the mesh network to permit efficient synchronization of the radio resources allocated to the network. The manner by which the synchronization

is provided permits a mesh network utilizing more than one synchronization source to effectuate time synchronization as well as also to provide a reference to various destination nodes.

Figure 2 illustrates timing circuitry, shown generally at 20, 5 of an embodiment of the present invention. The timing circuitry is functionally represented and can be implemented in any desired manner, both software implementations, hardware implementations, and combinations both hardware and software implementations. In the exemplary implementation, the timing circuitry 20 is implemented at one or more of the nodes of the of the mesh network. In the implementation shown in Figure 1 which shows a signal reference formed of the communication station forming the node 12-C, the timing circuitry is formed at least at the reference node 12-C. To permit synchronization of data packets communicated over several hops between nodes, other of the communication stations forming others of the nodes also includes the timing circuitry 20. 10 15

The circuitry 20 includes a network time register 22 of a register size capable of buffering a clock value which defines a reference time. An input clock signal here generated on the line 20 24 is applied to the register 22 to alter the buffered time reference value stored in the register.

Time reference values maintained at the register 22 are accessible, here by a data formatter 26 to retrieve the reference values buffered at the register 22 and to add values representative of the time reference values to data packets into which data 5 formatted by the data formatter is formatted. The time reference values form time stamps. And, the time stamp is representative of a reference time and is included in the header portion of outgoing, or incoming, data packets. When added to an outgoing data packet, the time stamp information is added into the packet, and when added into an incoming data packet the time stamp information added as a separate indication of the reception time at which the data packet is received at the node at which the circuitry 20 is formed.

The time reference value buffered at the network time register 22 is incremented for each clock cycle of the clock signal applied thereto. Not all of the least significant bits of the buffered value need to be available if the precision time stamp value to be added to a data packet does not require that the least significant bit, or bits, be used. By selectively selecting the number of bits to be used in the time stamping function, the circuitry 20 can be 20 used over a broad range of frequencies, enabling different kinds of reference signals.

The circuitry 20 further includes a latch register 32. The latch register is coupled to the network time register 22 and is selectively operable to retrieve and latch in the latch register a time reference value buffered and maintained at the register 22.

5 The latch register latches a value of the time reference value buffered at the register 22 upon application of a trigger signal thereto on the line 34. Upon application of the trigger signal on the line 34 to the latch register 32, the contents of the network time register 22 are copied into the latch register 32 and maintained thereat. When the trigger signal is generated upon the occurrence of a selected event, the time reference valued stored at the latch register is representative of the time of occurrence of the selected event. Thereby, an accurate reading of when a certain event occurred is stored at the latch register 32. Access to the time of occurrence of the event is available for subsequent analysis or processing.

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Several output sources are able to be synchronized to a single input source thereby. The input source would, e.g., become a master of the network time register 22. Each of the time stamping

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circuity of the respective output sources are accessible to the network time register 22 in manners analogous to the manner by

which the time stamp circuitry of the data formatter 26 shown in Figure 1 is capable of accessing the time reference value buffered at the network time register 22. If the output sources are positioned at different devices, such as on different integrated 5 circuitry chips or different integrated circuitry boards, synchronization is obtained by providing the clock signal generated on the line 24 and the trigger signal applied on the line 34 on each of the output sources. The clock signal generated on the line generated on the line 24 provides a time base. And, by generating 10 the trigger signal upon the occurrence of the selected event, a time reference value is latched at the latch register. 15

Figure 3 illustrates the timing circuitry of a further embodiment of the present invention. Again, the timing circuitry includes the network time register 22 and the latch register 32. And, the network time register is coupled to a data formatter 26 which includes time stamping circuitry for selectively time stamping 20 selected data packets. The line 24 upon which the clock signal is generated for application to the register 22 is again shown.

Here, the timing circuitry 20 further includes a strobe 25 register 42. The strobe register 42 is coupled to the network time register and selectively buffers a value retrieved from the network

time register thereat. When the register counts out, a strobe signal is generated on the line 34 which forms the trigger signal which is applied to the latch register 32. In this implementation, the trigger signal causes a value of the period length between the 5 generation of two trigger signals to be written into the register 32, and the trigger signals are generated periodically with a high degree of accuracy.

Figure 4 illustrates circuitry 40 representative of a multiple-device configuration in which the timing circuitry shown 10 in Figures 2 or 3 are implemented. Here, a clock oscillator in which the timing circuitry shown in Figures 2 or 3 are implemented.

Here, a clock oscillator 41 generates a clock signal on the lines 24 which are applied to clock pins 42 at circuit devices 44, 46 and 48. A trigger signal, generated at the circuit device 48 is applied to strobe pins 52 of the devices 46 and 48. The circuit 15 devices 44, 46, and 48 are representative of any of a large variety of devices, such as a radio interface, ethernet and a GPS (global positioning system) receiver.

Figure 5 illustrates clock synchronizations circuitry 60 which 20 includes the timing circuitry 20 shown previously in Figures 2 and 3. Here, a reference clock signal is generated by a voltage-

control clock oscillator (VCXO) 62. The clock signal is applied to the timing circuitry 20. And, time stamping is provided by the timing circuitry. The circuitry 60 also includes interface circuitry 64 which generates a biasing signal on the line 66 for 5 application to the clock oscillator. The physical interface circuitry 64 tracks the frequency of an incoming signal. If the incoming signal is a synchronization reference signal, a biasing signal is generated on the line 66 to alter the oscillation frequency of the clock oscillator 62. When the oscillation frequency of the reference clock signal is corrected, the correct reference clock frequency is obtainable from the physical signal itself, or at least a calculation of the offset. When the reference clock biasing is available, the device is capable of adjusting its own reference to match the reference of the network. 10 15

Figure 6 illustrates a method flow diagram, shown generally at 70, of the method of operation of an embodiment of the present invention by which to time stamp a data packet with a time reference value buffered and maintained at a network time register 22 (shown Figures 2 and 3).

20 First, and as indicated by the block 72, transmission of data packets between first and second communication stations formed of

nodes of a wireless mesh network is initiated. As indicated by the block 74, a burst of data packet is generated. Then, and as indicated by the decision block 76, a determination is made as to whether a time stamp is to be added to a data packet of the burst.

5 If so, the yes branch is taken to the block 78 and a time stamp is added to the data packet. If, conversely, a time stamp is not to be added to the data packets of the burst, no branch is taken to the decision block 82. A path is also taken from the block 78 to the decision block 82.

10 At the decision block 82, a determination is made as to whether hop information is to be also added to a data packet. If so, the yes branch is taken to the block 84, and a hop value associated with a number of hops is added to the data packet. A branch is then taken to the decision block 86. If, conversely, hop information is not to be added to the data packet, the no branch is also taken to the decision block 86.

15 At the decision block 86, a determination is made as to whether event timing information is to be added to the data packet.

20 If so, the S branch is taken to the block 88, and timing information is added to the data packet, and a branch is taken to the block 92. If the no branch is taken from the decision block

86, a branch is also taken to the block 92. At the block 92, the data packet burst is transmitted. Then, a path is taken to the end block 94.

Figure 7 illustrates a method, shown generally at 100, of an embodiment of the present invention by which to utilize a time stamp added to a data packet which is received at a second communication station forming a node of a mesh network, such as a mesh network shown in Figure 1. The time stamp information is utilized to synchronize the second communication station to the first communication station from which the data packet is sent.

First, subsequent to the start reception block 102, a data burst is received, indicated by the block 104. A receive time stamp is added to the data packet, indicated at the block 106, to identify the reception time at which the data packet of the data burst is received.

Then, and as indicated at the decision block 108, a determination is made as to whether an attempt should be made to synchronize the second communication station to the first communication station. If no attempt is to be made, the no branch 20 is taken to the end block 112. Otherwise, the yes branch is taken to the block 114 and a hop value is extracted from the data packet.

Then, and as indicated by the block 116, a determination is made as to whether the source of the burst of data packets is the reference in a pseudo-hierarchical structure defined in the mesh system. If not, the no branch is taken to the end block. Otherwise, the yes 5 branch is taken to the block 118 and the transmit time stamp contained in the data packet is extracted. Then, and as indicated by decision block 122, a determination is made as to whether timing information related to the occurrence of an event is available. If so, the yes branch is taken to the block 124 and the timing 10 information is extracted from the data packet. Then, a branch is taken to the block 126. The no branch from the decision block 122 is also taken to the block 126.

At the block 126, the time stamps are compared. Then, at the decision block 128 a determination is made as to whether the time 15 stamps correspond. If so, the yes branch is taken to the end block 112. Otherwise, time synchronization is performed by taking the no branch to the block 132 and the timing information at the second communication station is set using the time information extracted from the data packet received at the communication station.

20 Figure 8 illustrates signaling between two of the communication stations forming nodes in the mesh network 10 shown

in Figure 1 pursuant to synchronization operations effectuated during operation of an embodiment of the present invention. Here, data packets are communicated between the reference node 12-C and a node 12-1 positioned at a one-hop distance away from the reference 5 node. A data burst including at least one data packet to which a time stamp has been added in manners as above described, is sent by the reference node to the 12-C, as indicated by the arrow 122. The data packet is received at the node 12-1, and the time stamp information is extracted therefrom, also as described above. An acknowledgment burst is returned by the node 12-1 to the reference node 12-C, here indicated by the segment 124. By providing the acknowledgement burst back to the reference node, the propagation delay in the propagation of the data from the reference node to the node 12-1. When the acknowledgement packet is received at the reference nodes 12-C, a cumulative timing error corresponding to 10 twice the propagation delay is contained in the signal. The reference node is able to calculate the propagation delay responsive to the timing information contained in the acknowledgement packet and thereafter generate a message, here 15 represented by the segment 126, which includes a correction factor 20

correcting for the propagation delay. Thereby, the node 12-1 becomes completely time synchronized with the reference node.

Multiple-hop communication of a data packet between successive nodes of the mesh network shown in Figure 1.

5       Transmission of the data packet occurs during a time slot. First, for instance, the reference node 12-C is sent to a node 12-1. The transmission of the data packet is advanced by the propagation time required to transmit the data packet to the nodes 12-1. The packet transmission is initiated prior to the start of the slot. The node 12-1 passes on the data packet to a subsequent node, e.g., a node 12-2. And, transmission by the node 12-1 occurs at the start of the time slot due to the propagation delay in transmission from the reference node to the node 12-1. Then, once received at the subsequent node 12-2, the data packet is forwarded on to another of the nodes, e.g., a node 12-3. The propagation delay in communication of the data packet between the nodes 12-1 and 12-2 causes additional delay prior to forwarding the data packet to the node 12-3.

Thereby, through operation of an embodiment of the present  
20 invention, a manner is provided by which to provide accurate time reference indicia to the nodes of the mesh network to permit time

and clock synchronization pursuant to a pseudo hierarchy using one or more references.

The previous descriptions are of preferred examples for implementing the invention, and the scope of the invention should 5 not necessarily be limited by this description. The scope of the present invention is defined by the following claims.